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TITLE: Mars Relay Satellite Orbit Design Considerations for Global Support of Robotic Surface Missions

ABSTRACT:

This paper discusses orbit design considerations for Mars relay satellite (MRS) support of globally distributed robotic surface missions. The orbit results reported in this paper are derived from studies of MRS support **for two** types of Mars robotic surface missions: 1) the Mars Environmental Survey (MESUR) mission, which in its current definition would deploy a global network of up to 16 small landers, and 2) a Small Mars Sample Return (SMSR) mission, which includes four globally distributed landers, each with a return stage and one or two rovers, and up to four additional sets of lander/rover elements in an extended mission phase.

Mars relay satellites can provide important benefits in the support of such missions. Among the potential benefits are significant improvements in overall communications link performance and global connectivity, use of simpler, lower performance telecom subsystems for the surface mission elements, and reduced demands on Earth-based tracking stations.

The key requirements of the missions studied that are important from the standpoint of MRS orbit design include the following:

- For each of the two missions studied, a single MRS is to be capable of providing the required relay support for the full complement of landed elements deployed by that mission. A second MRS may be included for backup.
- Virtually full global coverage is required for both mission types. The MESUR mission landers may be deployed over the full range of

latitude and longitude. The SMSR lander/rover sets may be deployed anywhere to within 5° of the poles.

- Both missions require a relatively high data return of about 10 Mb/s from every lander each Mars day (sol). In addition, the SMSR mission calls for at least two communications periods/sol for each lander/rover set to allow a full Earth-in-loop operational cycle/sol; one communications period around sunset for data return to Earth for analysis and planning of the next sol's activity, another communications period near sunrise to allow uplinking of commands from Earth.
- The MRS support must be compatible with relatively simple lander design and operations.
- Both missions require that the MRS be launched on a relatively low cost launch vehicle.

Several different types of Mars orbits were initially considered for providing global coverage, including both circular and elliptical orbits with short to long orbit periods and inclinations from about 50° up to polar. Representative candidates of these types of orbits were evaluated with respect to several parameters, which relate directly or indirectly to the mission requirements. The most important of these parameters include: contact times and relative data return capability per sol versus surface location, Earth and Sun occultation frequency and duration, MRS mass delivery capability into orbit for specific launch vehicles, and orbit stability. The paper presents a summary of the results of analysis and tradeoffs of these orbit parameters. ~~is presented~~. Examples are provided below.

Surface contact times were evaluated by generating data of the types shown in Figs. 1 and 2. Figure 1 illustrates contact times versus longitude during a sol for a particular latitude. This type of data clearly shows the duration and regularity of individual contact times. Plots of the type shown in Figure 2 provide statistical summations of global contact times. The evaluation of contact times clearly demonstrated the regularity of surface coverage provided by inclined circular orbits.

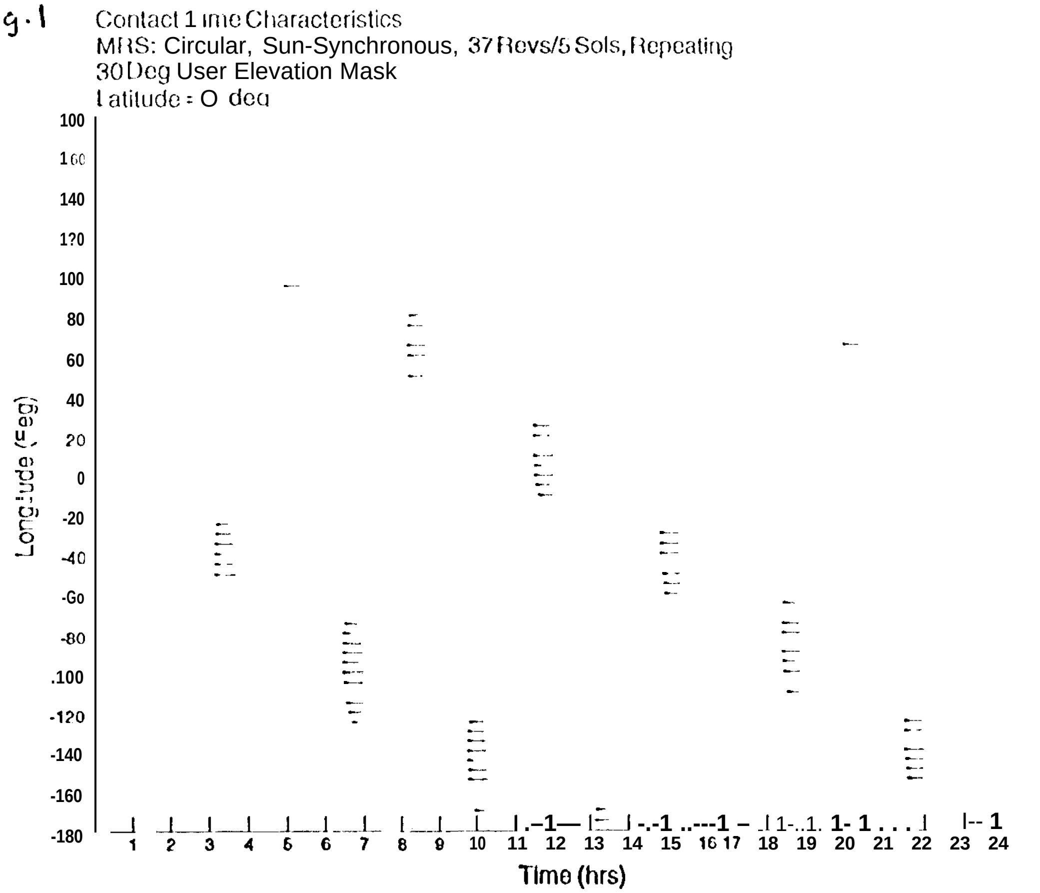
While consideration of contact times by itself is important in the design and operation of a mission, the factor of range must also be taken into consideration to evaluate potential data return capability. In the comparison of data return between the orbit types, a number of telecommunications parameters (e.g., lander transmitter power) could be assumed fixed, but other parameters (e.g., lander and MRS antenna beamwidths) were treated as variables. Figure 3 compares data return results for three types of orbits. In this comparison, variable telecommunications data rate is considered, as variable data rates can be employed to enhance data return when communications range varies. As indicated in Figure 3, the candidate elliptic orbit benefits most from variable data rates; however, variable rates involve design and operations complexities. Another illustration of data return is provided in Figure 4, in which a class of circular, sun-synchronous orbits is compared as a function of site latitude. This type of data permits selection of desired balance between equatorial and polar regions. The class of circular, sun-synchronous orbits compared in Figure 4 was found to include attractive candidates for MRS global support. The periods and inclinations of many of the orbits in this class are shown in Figure 5.

Figure 6 presents comparative results for another important operational parameter, namely MRS-Earth occultations. Data is shown for individual occultation occurrences as well as the aggregate of occultations experienced in a full sol. 7 he data of Figure 6 shows very favorable results for example candidates from the circular, sun-synchronous class of orbits (21 and 22 Revs per 5 sols repeat orbits). The paper will also include the results of similar analyses for sun occultations of the MRS.

The results of analysis of MRS delivery capability into orbit will also be included in the paper. An example of results of this type of analysis is provided in Figure 7, in which delivered mass capability is shown for the 2003 Mars launch opportunity with delivery into a circular, sun-synchronous 22-rev/5 sol repeat orbit using a Delta 7925 launch vehicle. Both total dry mass, including propulsion system, and net mass are shown, and an optimum launch period is identified assuming a constant propellant load.

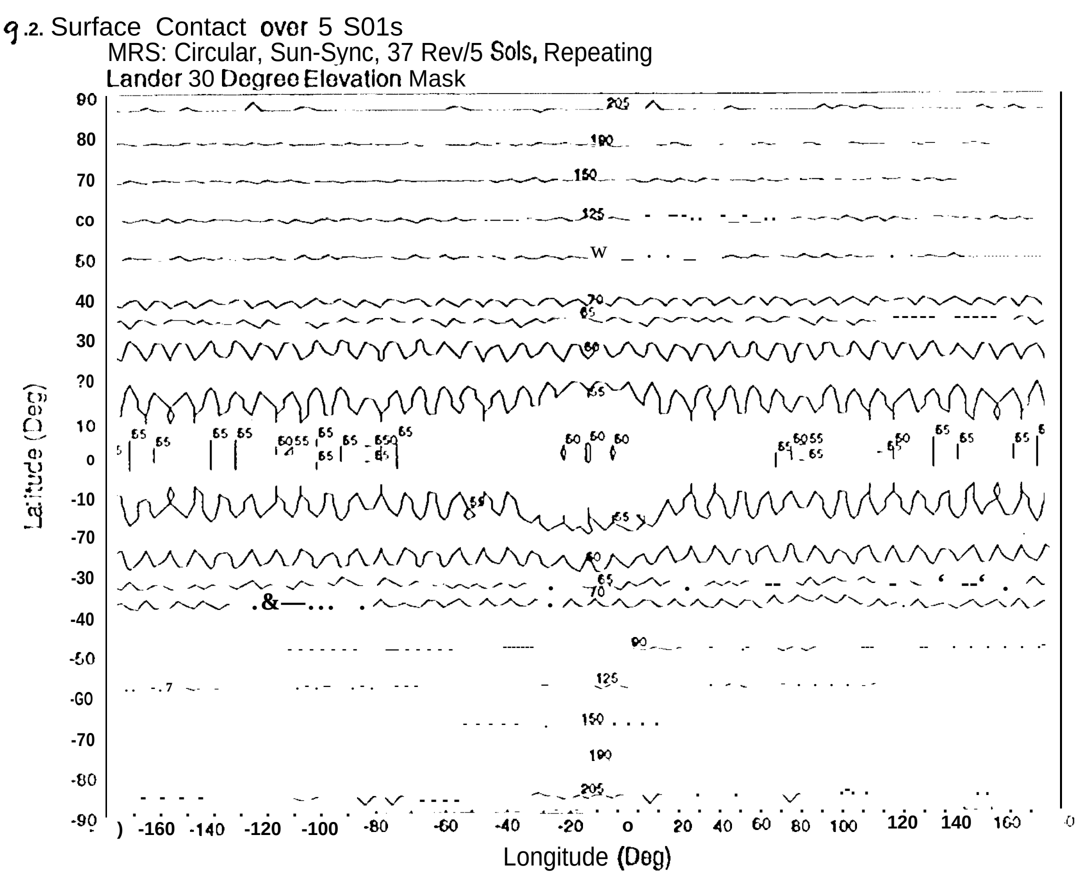
Mars arrival conditions are also an important consideration from the standpoint of orbit orientation. For example, orbit orientation in terms of the ascending node relative to the day/night terminator influences the occultation characteristics and timing of communications periods relative daylight operations. Table 1 is an example of results for orbit orientation analysis. For the case shown in Table 1 (circular, sun-synchronous 22-rev/5 sol repeat orbit), a very small node offset is achieved at arrival without inducing apsidal rotation.

Fig. 1



Contact Time Characteristics
MRS: Circular, Sun-Synchronous, 37 Revs/5 Sols, Repeating
30 Deg User Elevation Mask
Latitude = 0 deg
Longitude (Deg)
Time (hrs)

Fig. 2.



Surface Contact over 5 Sols
MRS: Circular, Sun-Sync, 37 Rev/5 Sols, Repeating
Lander 30 Degree Elevation Mask
Latitude (Deg)
Longitude (Deg)

Fig. 3 DATA RATE/QUANTITY COMPARISONS BETWEEN ORBIT TYPES
MRS: 67 DEGREE BEAMWIDTH, LANDER: HEMISPHERICAL ANTENNA, 1W TX POWER

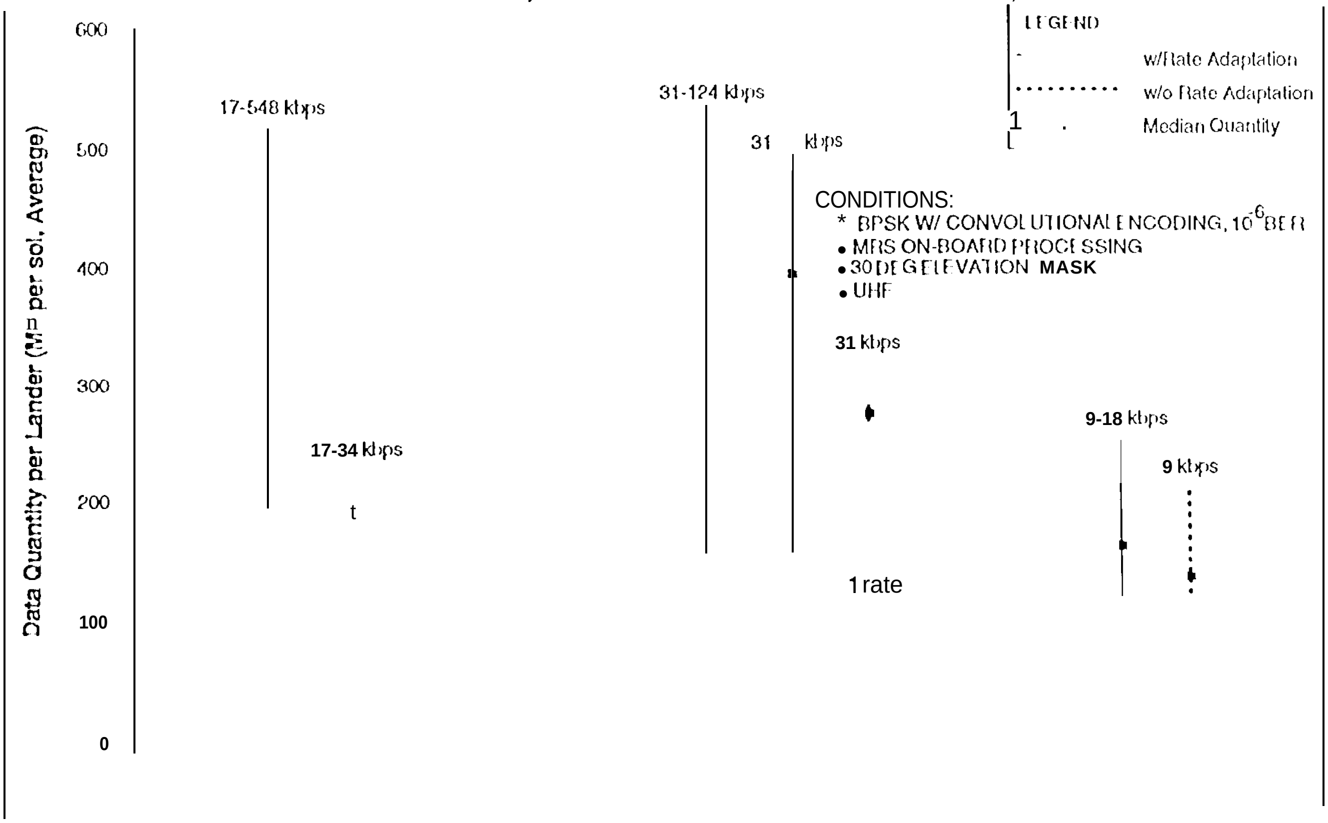
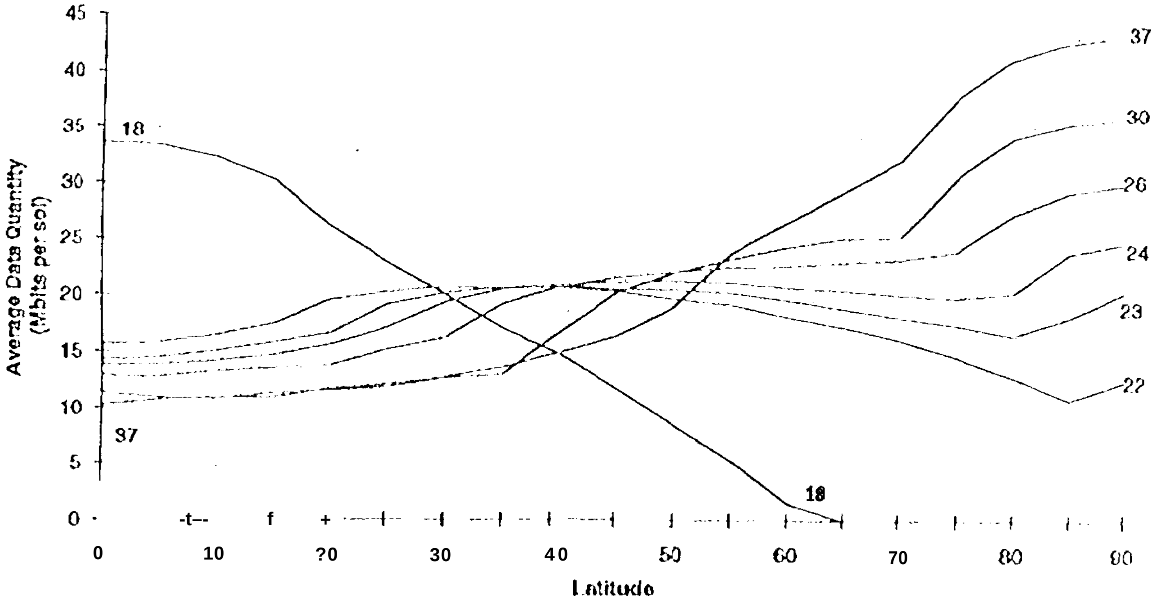


Fig. 4 Average In Situ Return Data Quantity per Sol per Lander versus Latitude
Average over 5 Sols, for Various Circular, Sun-Synchronous MRS Orbits
(Results are Symmetrical about the Equator)



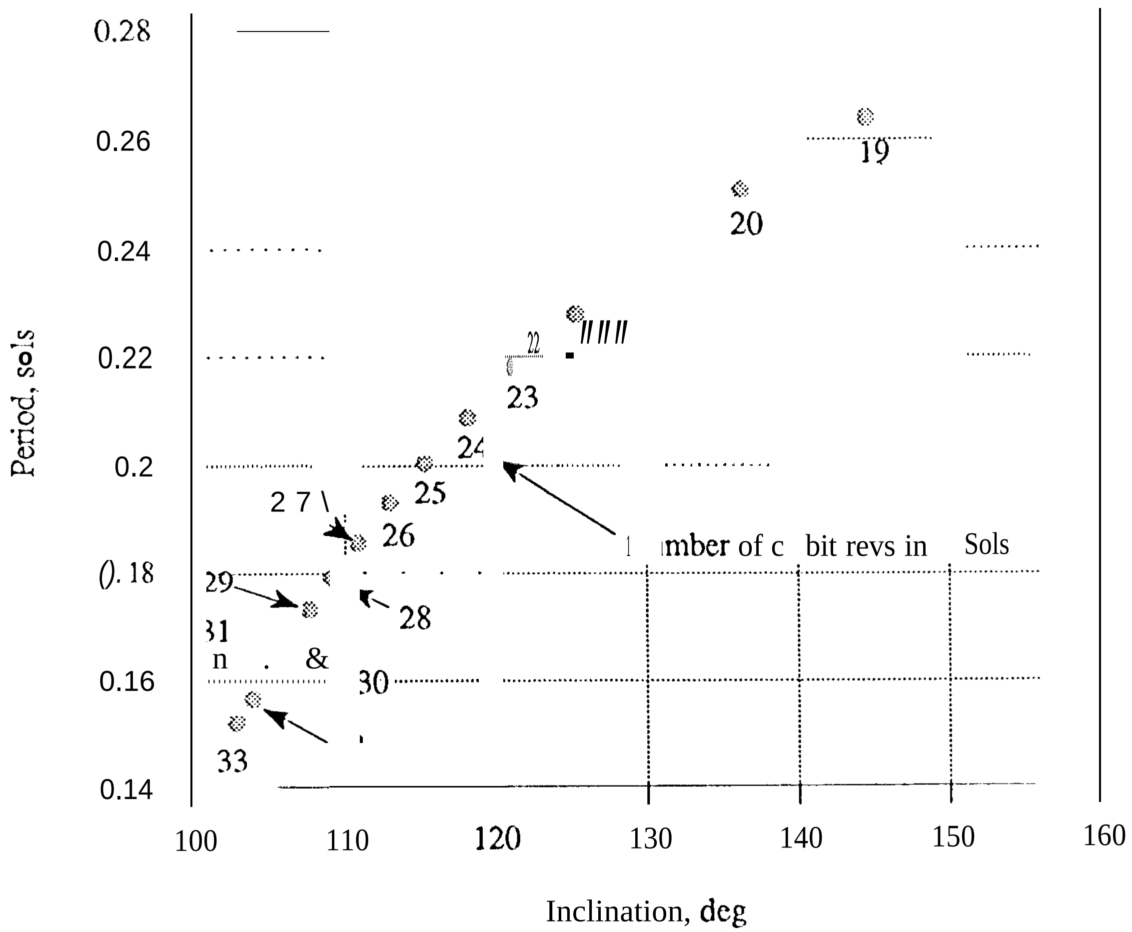


Fig. 5 **Sun synchronous S-sol repeat orbits**

Fig. 6 STATISTICS OF MRS-TO-EARTH LINK

OCCULTATION

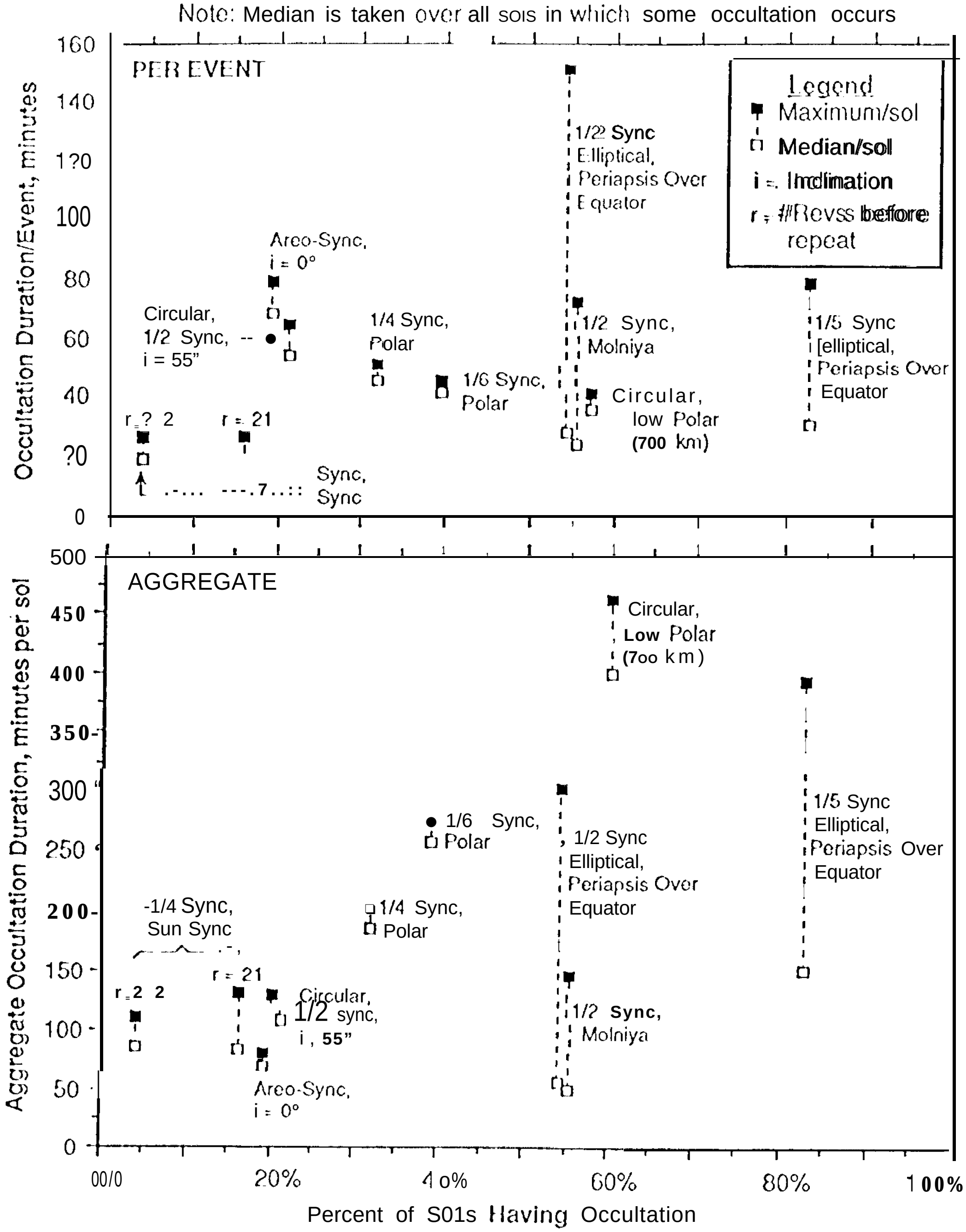


Fig. 7 MAXIMUM DRY MASS vs LAUNCH DATE for a CONSTANT PROPELLANT LOAD

.2003 Opportunity - Circular 2? Revs /5 S0/s Orbit

Delta 7925 Performance

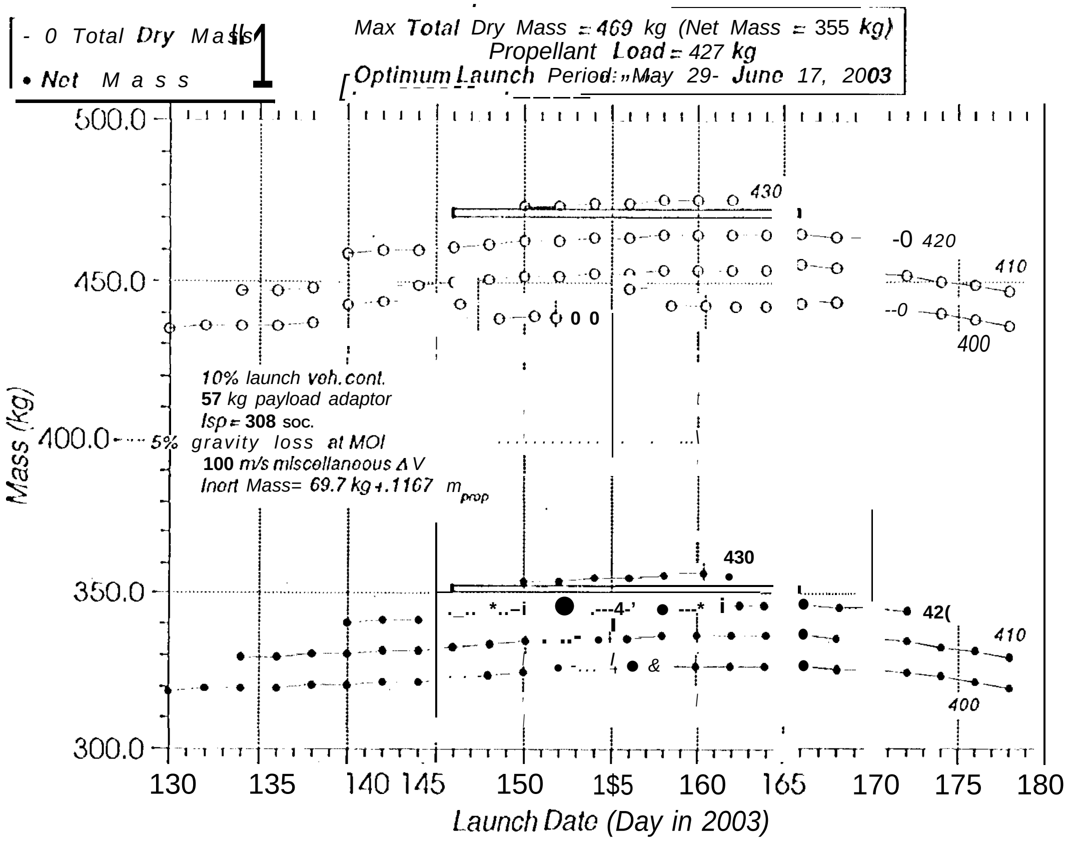


Table 1. 2003 LAUNCH PERIOD and ARRIVAL CONDITIONS

Launch Date	Arrival Date	C3 (km^2/s^2)	DLA	VHP (km/s	Insertion	Node Offset*
5-29-2003	12-24-2003	9.228	-6.100	2.716	south	7.0" East
6-.7-?003	12-25-2003	8.955	-5.700	2.708	South	6.3° Fast
6-6-2003	12-27-2003	8.825	-5.500	2.702	south	5.4" East
6-10-2003	12-31-2003	8.851	-5.500	2.699	South	4.3° East
6-14-.2003	1-1-2004	9.048	-5.700	2.698	south	3. O" East
6-18-2003	1-3-2004	9.432	-5.900	2.702	south	1.4° East

* Angle from 6 PM point 10 Ascending Node

No broken plane maneuvers

Launch Vehicle	Max Total Dry Mass	Max Net Mass	Propellant load
Delta 7925	469 kg	355 kg	469 kg
Atlas IIAS	870 kg	701 kg	792 kg

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MARS RELAY SATELLITE ORBIT DESIGN CONSIDERATIONS FOR GLOBAL SUPPORT OF ROBOTIC SURFACE MISSIONS

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MARS RELAY SATELLITE ORBIT DESIGN CONSIDERATIONS FOR GLOBAL SUPPORT OF ROBOTIC SURFACE MISSIONS

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This paper discusses orbit design considerations for Mars relay satellite (MRS) support of globally distributed robotic surface missions. The orbit results reported in this paper are derived from studies of MRS support for two types of Mars robotic surface missions: 1) the Mars Environmental Survey (MESUR) Network mission, which would deploy a global network of up to 16 small landers, and 2) a Small Mars Sample Return (SMSR) mission, which includes four globally distributed landers, each with a return stage and one or two rovers, and up to four additional sets of lander/rover elements in an extended mission phase.

Several different types of Mars orbits were considered for providing global coverage, including both circular and elliptical orbits with short to long orbit periods and inclinations from about 50° up to polar. Representative candidates of these types of orbits were evaluated with respect to several parameters, which relate directly or indirectly to the mission requirements, The most important of these parameters include: contact times and relative data return capability versus surface location, Earth and Sun occultation frequency and duration, MRS mass delivery capability into orbit for specific launch vehicles, orbit orientation, and orbit stability. The paper presents a summary of the results of analysis and tradeoffs of these orbit parameters.

INTRODUCTION

Recent years have witnessed a rebirth of interest in NASA's long term mission of exploration. Although the prioritization of objectives and corresponding mission sets is still being debated as part of the political process, an emphasis on the robotic exploration of the planet Mars does seem to be emerging as the focus of a new concensus. Given the essential role that telecommunications plays in space missions, whether robotic or piloted, it is prudent to consider the options for providing this needed function in the context of future missions to Mars. One means of enhancing, or even enabling, communications between Earth and Mars that was recognized early in the consideration of options is use of a Mars relay satellite. Such a satellite is the only means of providing connectivity with elements on the martian surface that are out of line-of-sight contact with the Earth. These include elements on the backside, which are out of communication for a part of every day, and elements at the poles, which can be out of communication for months at a time.. A relay satellite also contributes telecommunications

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performance advantages because it can be economically designed to have high data rates both with elements on the planet's surface and also with the Earth. This permits significant relaxation of the telecommunications performance, requirements on surface. elements, of which them may be. many, and avoids the need to fly and land high mass, high power, and expensive telecommunications systems, It also tends to place a smaller load on the Earth-based tracking resources of the Deep Space Network. Finally, a relay satellite in Mars orbit can be profitably used as a navigation beacon for other spacecraft approaching the planet. This paper reports on the issues that affect the selection of orbits for Mars relay satellites, and documents the key trades that have been examined as well as specific orbits designed to meet the requirements of representative missions, Early work traces back to the NASA 90-Day Study[1] and the report of the Synthesis Group.[2] Detailed designs are shown for the Small Mars Sample Return Mission [3] as well as for the network of landers known as the Mars Environmental Survey or MESUR [4].

REQUIREMENTS

The key requirements of the missions studied that are important from the standpoint of MRS orbit design include the following:

- For each of the two missions studied, a single MRS is to be capable of providing the required relay support for the full complement of landed elements deployed by that mission. A second MRS may be included for backup.
  - The MESUR Network mission consists of up to 16 globally distributed small landers.
  - The SMSR mission includes four globally distributed landers, each with a return stage and one or two rovers, and up to four additional sets of lander/rover elements in an extended mission phase,
- Virtually full global coverage is required for both mission types. The MESUR mission landers may be deployed over the full range of latitude and longitude. The SMSR lander/rover sets maybe deployed anywhere to within 5° of the poles.
- Both missions require a relatively high data return of about 10 Mb/lander each Mars day (sol). In addition, the SMSR mission calls for at least two communications periods/sol for each lander/rover set to allow a full Earth-in-loop operational cycle/sol; one communications period around local Mars sunset for data return to Earth for analysis and planning of the next sol's activity, another communications period near sunrise to allow uplinking of commands from Earth.
- The MRS support must be compatible with relatively simple lander design and operations.
- Both missions require that the MRS be launched on a relatively low cost launch vehicle.

ORBIT TYPES AND GENERAL CHARACTERISTICS

Several different types of Mars orbits were evaluated for providing global coverage and meeting the mission requirements. Included were both circular and elliptical orbits with short to long orbit periods and inclinations from about SO° up to polar. Table 1 provides a summary of the orbits evaluated and their key characteristics.

The elliptical orbit examples chosen for evaluation have the "critical" value of inclination (63.4°) in order to preserve apse line orientation. In addition to a "Molniya" type orbit, with argument of periapsis equal to 90°, two elliptical orbits were chosen with apse line in the equatorial plane to provide symmetric surface coverage. One of these is designed to repeat after 26 revolutions in S SOIS, and was selected for an early MESUR mission study conducted by Ames Research Center with orbit analysis support from Science Applications International Corp.[5] This orbit has its apse line along the line of nodes to provide symmetric coverage of north and south latitudes.

Table 1. ORBIT TYPES EVALUATED FOR MARS RELAY SATELLITE

Orbit Type	Altitude, km	Inclination, deg	Remarks
Elliptical			
• 1/2 Mars synchronous, "Molniya", apse line normal to line of nodes	400 x 18544	63.4°	"Critical" inclination
• 1/2 Mars synchronous, apse line in equatorial plane	400 x 18544	63.4°	"Critical" inclination
• 26-rev/5-sol repeat orbit, apse line in equatorial plane	400 x 6392	63.4°	"Critical" inclination
Circular			
• 1/2. Mars synchronous, inclined	9471	55°	
• 1/4 Mars synchronous, polar	4710	90°	
• 1/6 Mars synchronous, polar	2789	90"	
• 1/11 Mars synchronous, polar	700	90°	
• Sun-synchronous, family of repeat orbits, 18- to 50-rev/5-sol* "	5315 to 1003	158 to 95	Also refer to Figures 1 & 2

* These orbits can be made "frozen" by choosing appropriate eccentricity values of less than 0.006.

The circular orbit examples include a range of polar orbits and a family of sun synchronous repeat orbits. The repeat cycle of the family of sun synchronous orbits varies from 18 to 50 revs in a *5-sol* period, The altitude and inclination parameters for several of the sun synchronous orbits are depicted in Figure 1. Values of altitude and inclination for the complete family of sun-synchronous orbits that were evaluated are plotted in Figure 2. As discussed later, in the Orbit Stability section of this paper, the sun-synchronous orbits can be "frozen" if they are made slightly non-circular by selecting very small values of eccentricity (< 0.006), as appropriate for the specific orbit.

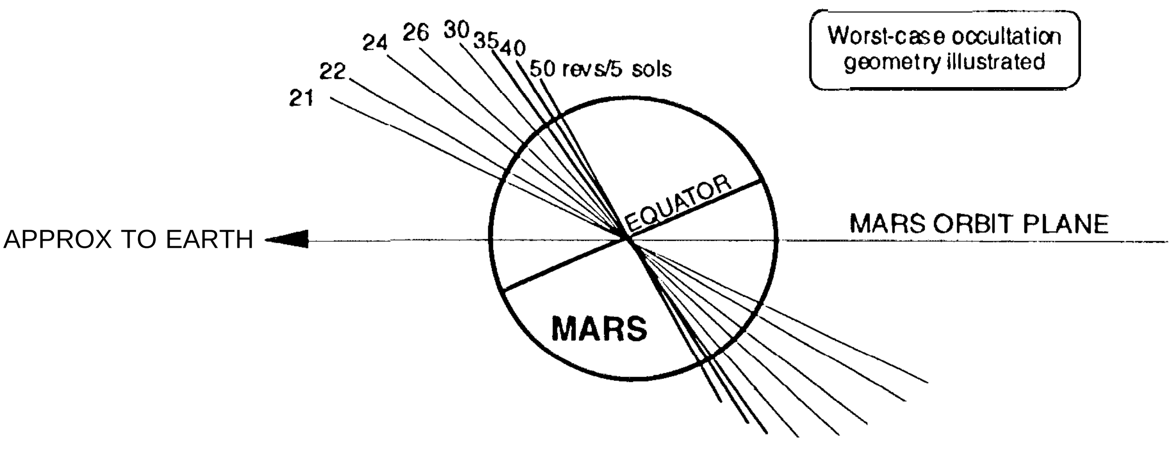

Figure 1. Sample Circular, Sun-synchronous MRS Orbits

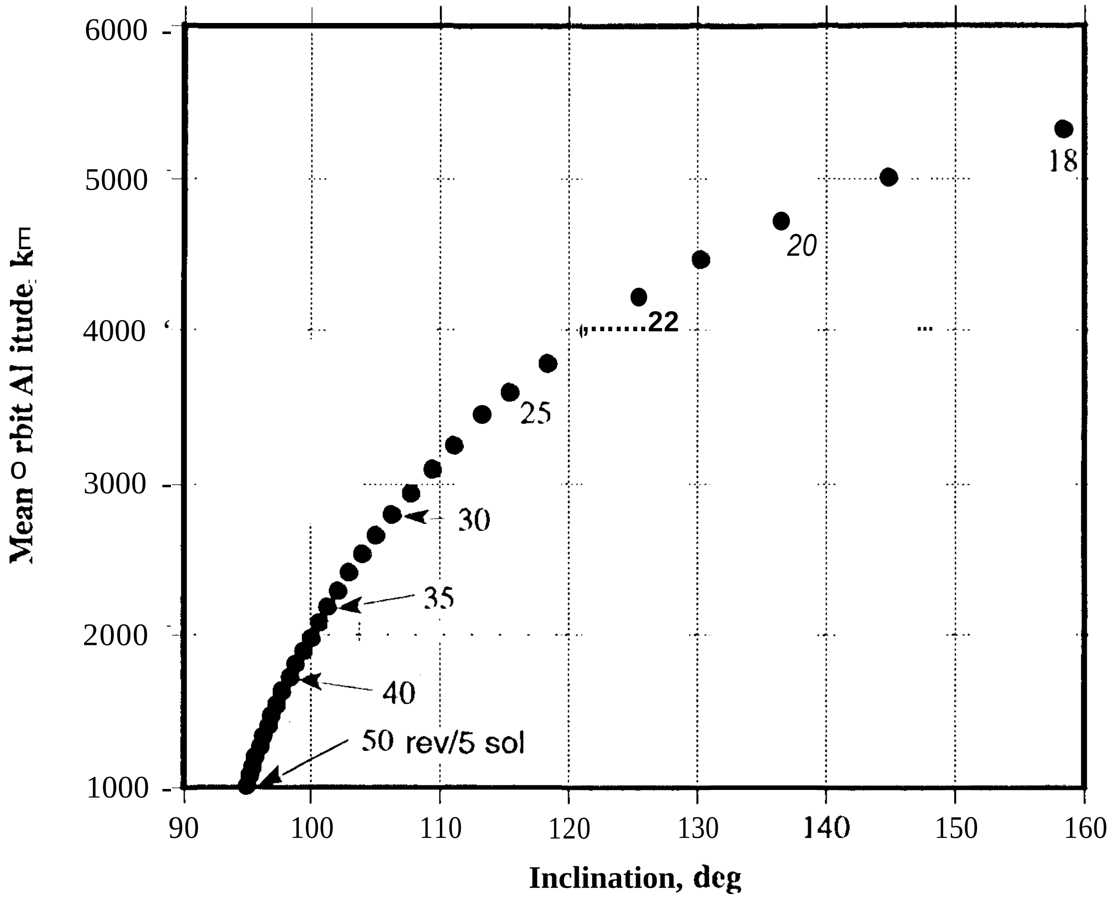

Figure 2. Altitude and Inclination of Sun-Synchronous, Repeat Orbits

RELAY SATELLITE IN-SITU SURFACE COVERAGE

A key factor driving MRS orbit selection is available contact time between the MRS and mission elements on the surface. In both missions considered, MRS contact to each surface element is required every sol. Additionally, the SMSR mission has an operational requirement for two MRS contacts each sol for each lander/rover set -- one near local Mars sunset for data return to Earth, and a second near sunrise for command uploads. Finally, total contact time available for each surface element is a significant factor establishing surface element data return capability. Because the Mars elements in each mission can be globally distributed, and a final set of element locations may not be determined until late in the planning process, the MRS orbit needs to satisfy these contact requirements across the surface of Mars.

Figure 3 illustrates sample results of surface coverage analyses showing contact time per sol across the entire surface of Mars for one of the circular, sun-synchronous repeat orbits (22-rev/5-sol). Plotted results represent average coverage per sol, averaged over 5 SOIS assuming surface element-to-MRS visibility whenever the MRS is 30° or more above the horizon. This elevation restriction conservatively accounts for potential obstructions near the surface clement and surface element tilt. As shown in the figure, this orbit provides approximately uniform coverage across the surface of Mars when coverage is averaged over 5 SOIS.

Figure 4 summarizes the range of contact times available over one sol for a number of the orbit types examined. The figure summarizes minimum contact times both across the entire surface of Mars and in a region within ±45° latitude of the equator of Mars. The figure demonstrates the large differences in available surface contact that occur as MRS orbit characteristics (period, inclination, and eccentricity) are varied. For example, as the orbit period

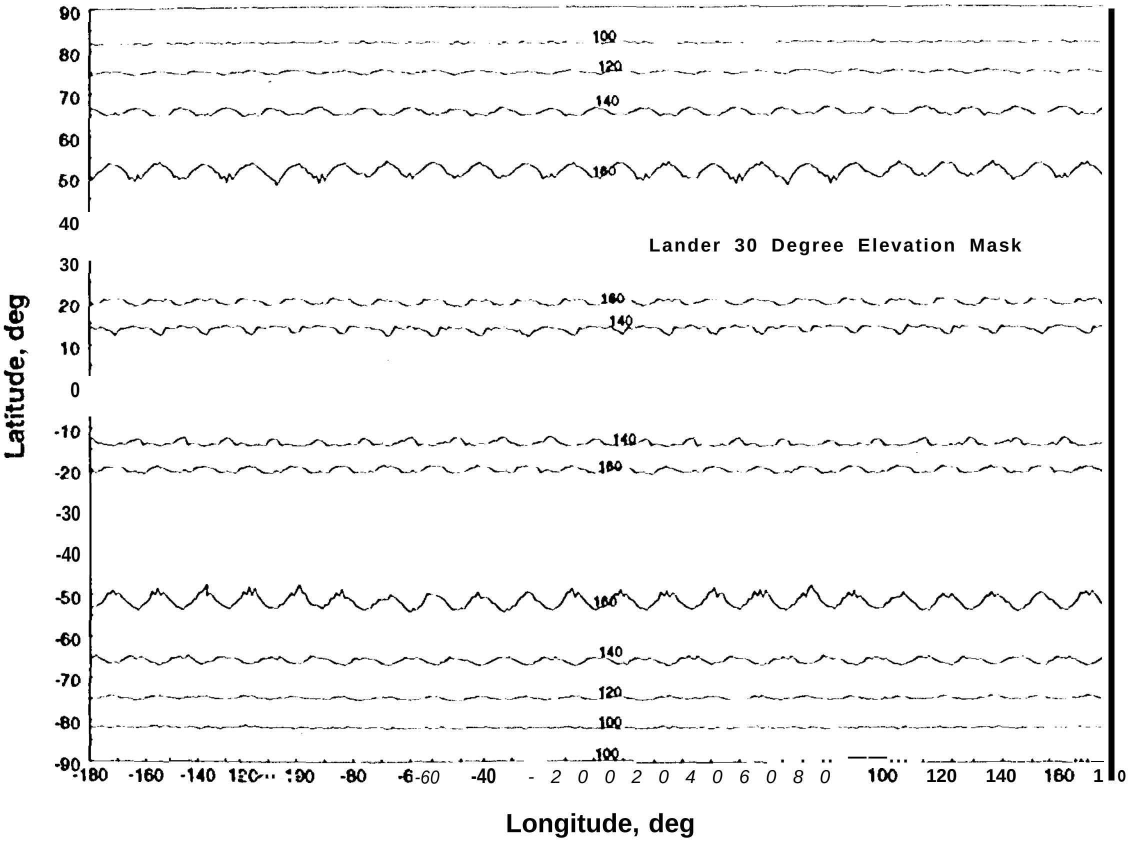

Figure 3. Surface Contact per sol, Averaged over 5 sols for the Circular, Sun-Synchronous 22-rev/S-sol Repeat Orbit

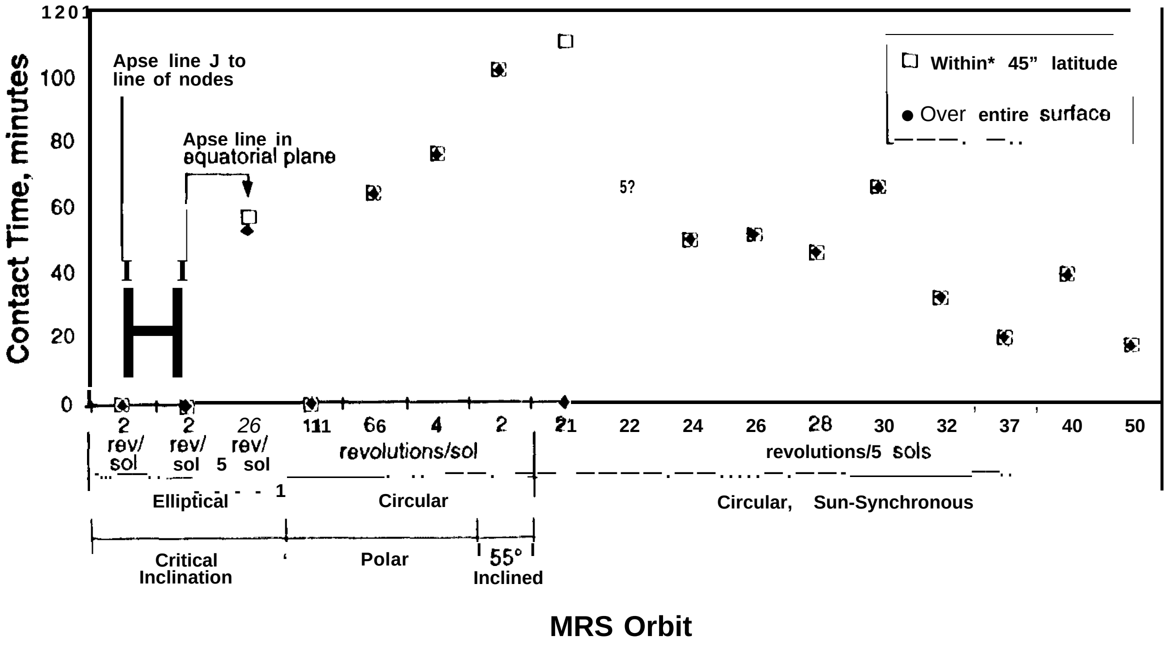

Figure 4. Minimum MRS Surface Contact over 1 sol

increases (e.g. the number of revolutions per sol decreases), the orbit altitude increases and more of the surface of Mars becomes simultaneously visible to the MRS. The net effect is to increase. the length of each surface-element contact interval while potentially decreasing the number of MRS contacts occurring per sol. Another impact of increased orbit altitude is more. subtle. Since increasing orbit altitude causes more of the surface of Mars to become visible, it also potentially increases the. number of surface elements simultaneously visible. from the. MRS. In this situation, MRS communications resources must either be time-shared among the visible users (resulting in an effective loss of contact time) or provision on board the MRS must be made for simultaneous support to multiple surface elements (resulting in increased MRS complexity).

Increasing orbit eccentricity (making the orbit more elliptical) tends to make surface coverage less uniform and results in complete loss of coverage to some surface locations if increased excessively. Such a loss of coverage occurs for the. two illustrated elliptical orbits having a period of 1/2 sol (2 revolutions per sol). Orbit inclination can be used to control polar contact. While a non-zero inclination is required to achieve some contact to the polar regions of Mars, an inclination near 90° can result in extra contact to the poles at the expense of contact to lower latitude. regions. For example., the. circular polar orbits illustrated in the figure all provide much greater coverage to the higher latitude regions than to the equatorial regions of Mars. The circular, sun-synchronous orbits also exhibit this effect. These orbits become more highly inclined as the number of revolutions pcr sol increases, The range of orbits examined extends from a 21 -rev/S-sol orbit which provides no polar coverage to the SO-rev/5-sol orbit which provides much greater coverage to the polar regions of Mars than elsewhere.

Figure 5 is a sample result applicable to the 22-rev/5-sol sun-synchronous orbit which adds a further degree of refinement to the analysis. For a single latitude of 0°, this figure provides visibility intervals for each longitude on the surface of Mars to the MRS. (The contact intervals at each longitude are indicated by the horizontal lines in the figure.) Such information is

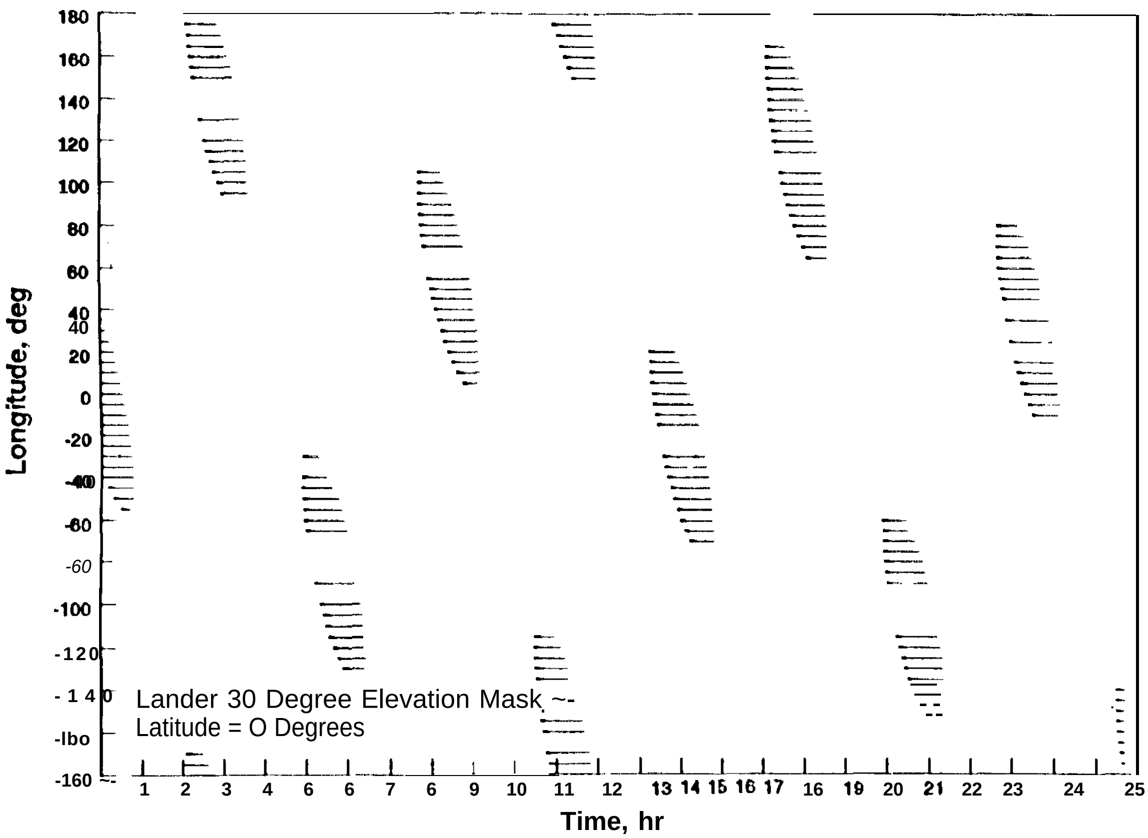

Figure 5. Contact Time Characteristics for for the Circular, Sun-Synchronous 22-rev/S-so} Repeat Orbit

necessary in evaluating the various orbit types with respect to the SMSR operational requirement for multiple contacts to each surface point every sol. As illustrated, this orbit provides two regularly spaced contacts to each surface. location along the equator of Mars. Using similar results applicable to a variety of latitudes for each orbit type permitted detailed evaluation of the orbits with respect to mission operational requirements. In particular, the circular, sun-synchronous family of orbits proved exceptionally well suited to the requirement for multiple surface contacts every sol. Furthermore, by aligning the right ascension of the ascending node for the orbit with the day-night terminator on Mars, these contacts can be made to generally occur at local Mars sunrise and sunset --- ideal for the command/data return operational cycle of the SMSR mission.

DATA RETURN CAPABILITY

Design of MRS and lander communications subsystems to meet the data return requirements for each mission requires analysis and understanding of a complex, multi-dimensional trade space. The fundamental communications requirement for both the MESUR and SMSR missions is the return of approximately 10 Mb data per day per lander. Key considerations impacting the MRS and surface elements relevant to achievement of this requirement include:

- The mass/power/volume available for communications.
- Radio frequency trades, including available. component technologies and performance.
- Operations requirements/goals such as the potential need for a backup link directly from the landers to Earth.
- Antenna trades, including the implementation and operational impacts of various antenna types/antenna pointing strategies,
- Communications strategies for multiple surface elements simultaneously visible. to the MRS.

Selection of an MRS orbit to meet the mission data return requirements must take into account all of these factors as well as their inter-relationships.

Antenna Options

Figure 6 illustrates the relevance of MRS orbit altitude to several of the key trades outlined above. The figure shows communications from/to the surface for two potential MRS orbit types -- a higher altitude circular orbit having a period of 1/4 sol, and a 1/5 sol period elliptical orbit at a lower altitude (near periapsis). For each MRS position illustrated, a region is drawn on the surface of Mars to indicate those lander positions which would be in view of the MRS, assuming 30° minimum elevation. Whether or not the MRS can view the landers in this region depends on the MRS antenna implementation. One option for the MRS is to maximize communications data rate via a high-gain, narrow-beamwidth antenna or even a phased array. However, with a sufficiently narrow beamwidth, the antenna beam would not include all of the lander-defined 30° mask region and would need to be steered to each lander's position in turn. Such steering not only limits MRS communications to a single lander at a time (with a resulting decrease in attainable contact time), but also introduces significant hardware and operational complexity to the MRS implementation. Such hardware complexity includes the need for a gimbaled antenna and associated control circuitry, while the burden associated with commanding the MRS antenna to point to the various lander sites as they come into view represents a significant added operational complexity.

A second antenna option is to use an MRS antenna beamwidth sufficiently wide. to assure coverage of all landers within the 30° mask region illustrated in Figure 6. This intermediate gain option would provide service to all landers that have visibility to the MRS without the need for steering to individual landers and the associated operational burden. The antenna would need to be pointed towards nadir, which in itself may represent a significant difficulty. To understand why, consider the fact that MRS communication with Earth will require an additional MRS antenna (necessarily high gain). To maintain one antenna pointed at Earth while another is pointed at Mars requires that at least one of the two antennas be gimbaled. Also note from the figure that the beamwidth (and corresponding performance) of an antenna sized to just cover the 30° mask region will depend on MRS altitude with higher altitude orbits permitting narrower antenna beamwidths and correspondingly higher antenna gains. The higher antenna gain can partially offset the impact of increased range to the higher altitude MRS when computing lander link performance (e.g., achievable. data rate) under fixed lander performance assumptions. Note that the increased range is not without some penalty. The narrower beamwidth implies a larger antenna and, depending on the frequency band used, at some point the antenna size becomes excessive. (For example, at 300 MHz UHF, a helix 12 feet long is required to create a beam sized just to cover the lander 30° mask region for the MRS in the 1/4 synchronous circular orbit.) Quantitative results regarding the. data quantity trades with respect to MRS altitude will be discussed below.

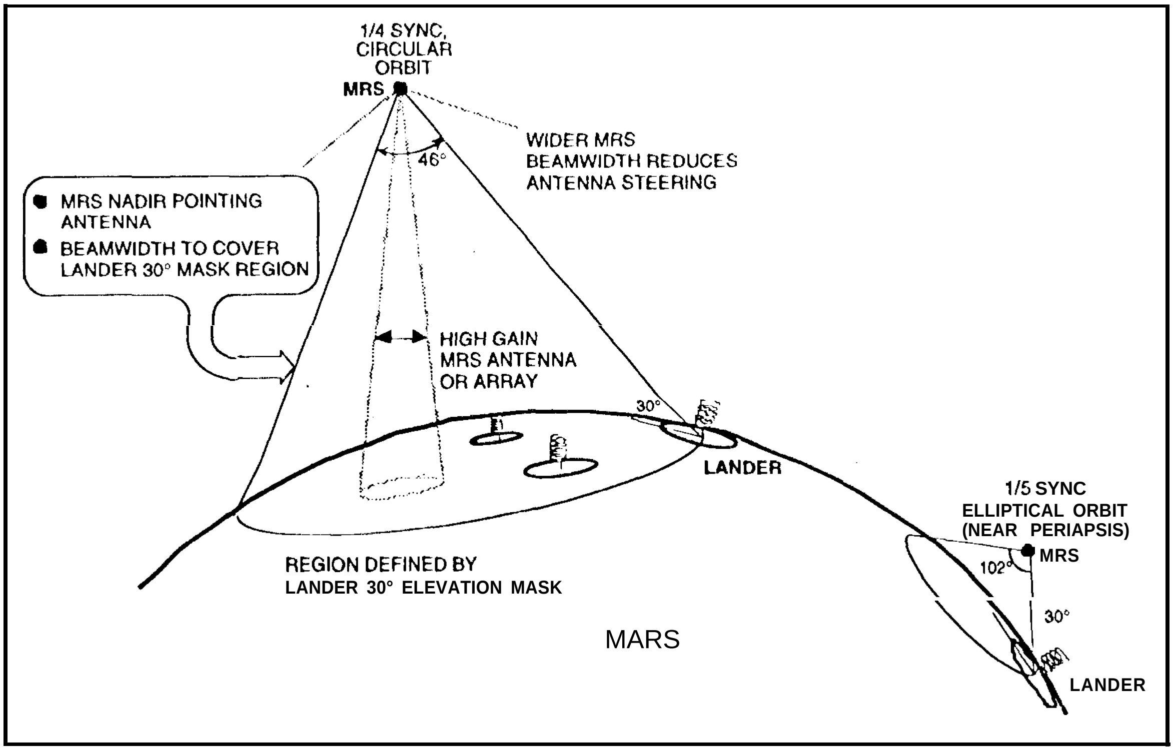

Figure 6. MRS Orbit Altitude/Antenna Beamwidth Trades

A third option is for an even wider beamwidth MRS antenna. While lowering gain and associated Performance below that achieved with the second option, the wider beamwidth reduces still further the MRS antenna pointing requirements. In 'the extreme, if the MRS has an omnidirectional coverage antenna (with identical performance in all directions) no gimbaling of the antenna would be required. In such an implementation, the antennas for both lander and Earth communications could be fixed to the MRS spacecraft body with potentially significant cost/complexity savings. (The MRS body itself could be pointed to keep one antenna oriented toward Earth). Omnidirectional coverage is usually implemented using a combination of two or more hemispherical coverage antennas. Note also that use of an omnidirectional antenna implies a fixed performance antenna regardless of MRS altitude —there is no factor to offset the degradations in achievable data rate that occur as altitude is increased as there was for the second antenna option.

The performance trades to date have focused primarily on the second and third antenna options discussed above. These options appear most attractive from a cost/complexity standpoint.

Fixed vs Variable Data Rate Options

Referring again to Figure 6, note. that the lander-to-MRS communications performance can vary both during a communications opportunity as the. MRS moves across the sky, and (for elliptical orbits) between communications passes as the MRS moves between apoapsis (maximum altitude) and periapsis (minimum altitude). The variation occurs both due to the changing lander-to-MRS slant range and, depending on the MRS and lander antenna types, the changing location of each in the other's antenna beam. The combination of these effects (range and antenna gain) can be quite. significant, resulting in dramatic variations in lander-to-MRS achievable data rates. For example, the lander-to-MRS slant range variation for the illustrated 1/5 synchronous elliptical orbit is sufficient to cause -24 dB variation in achievable link data rate if all other conditions arc held constant. For the circular orbit alternatives, the variation is somewhat less but still significant.

Two separate operational approaches for dealing with the performance variations outlined above merit consideration. One possibility is to ignore the changes in communications performance by using fixed lander and MRS communications parameters. In this instance, the link data rate must be sufficiently low to permit lander communications under the worst-case conditions or some communications opportunities must be sacrificed. A second possibility is to adapt the lander-to-MRS data rate to the changing link conditions -- using a higher rate when possible, but dropping back to a lower data rate when link conditions arc less than ideal. While the second approach clearly maximizes total data returned by the landers, the extent of the increase must be assessed relevant to the added MRS and lander implementation complexity. Figure 7 is a sample of one such assessment performed as part of the current study. The figure illustrates lander-to-MRS return link data quantity per sol for several different MRS orbit choices using various numbers of available data rates. For each orbit and number of available data rates, the figure illustrates the range of data return quantities (per lander) achievable across the surface of Mars. The MRS and lander implementations (other than the number of available data rates) are held fixed among all the plotted results. The MRS antenna beamwidth of 67° was found to be near optimum for the elliptical orbit (despite the loss of some coverage near periapsis), but a nadir oriented antenna with a narrower beamwidth could be used to improve performance for the two circular orbits. The plot demonstrates the importance of rate adaptation for elliptical MRS orbits.

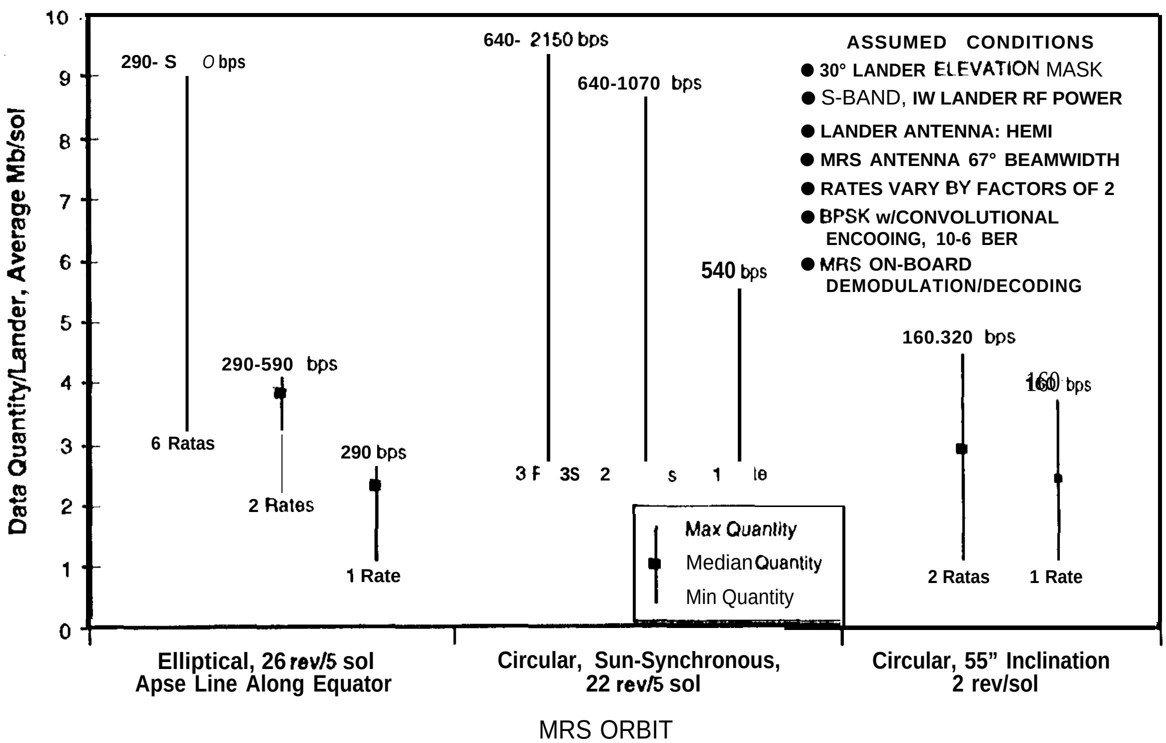

Figure 7. Lander-to-MRS Data Return Comparisons with Lander Rate Adaptation

As shown, the minimum data quantity achieved across the surface of Mars can be increased by nearly a factor of three using six rate levels for this particular orbit. But also note that the benefits of variable link data rates are not obvious for the circular orbits. While some locations on the surface of Mars substantially benefit by the usc of more than one communications rate, other surface locations receive no performance improvement for the circular orbits. But, for the 22 revolutions per 5 sols orbit, such performance enhancement appears unnecessary. This orbit can attain performance, without rate adaptation across much of the surface of Mars, which is comparable to that attained by the elliptical orbit with rate adaptation.

Radio Frequency options

Another important factor relevant to data return quantity driving MRS orbit selection is the selection of an RF frequency for use on the lander-to-MRS link. Of primary importance. is the impact of RF frequency on achieved link performance. This impact arises from the dependence of the various link parameters (e.g., antenna gain and free space losses) on the communications frequency. For the situations of greatest interest, decreasing the lander-to MRS link frequency results in improved performance. This is because the. MRS and landers are both required to provide coverage of a fixed region of space, implying a constrained antenna beamwidth for each element, With beamwidth held fixed as frequency is varied, MRS and lander antenna gain is also fixed. But , free space losses (e.g., the losses associated with path length) decrease as frequency decreases, resulting in a net improvement in performance. While other performance factors (e.g., amplifier noise) also depend on frequency, these factors tend to be less significant and do not reverse. this trend.

Decreases in frequency to improve link performance cannot be continued indefinitely. To hold antenna beamwidth fixed as frequency decreases, as described above, requires increasing antenna sizes. Additionally, the contributions of external noise sources (e.g., galactic noise) also increase as frequency is decreased. Ultimately a limit is reached beyond which further decreases in frequency become undesirable. Results to date have indicated that the UHF band can provide good link performance, but performance begins to suffer at the lower VHF band.

Figure 8 illustrates sample results from the current study applicable to UHF and S-band frequencies of operation. The graph illustrates lander RF power required to assure an average lander-to-MRS return data quantity of 10 Mb/sol (averaged over 5 sols) for all points on the surface. of Mars, for a variety of the circular, sun-synchronous MRS orbits. The results take into

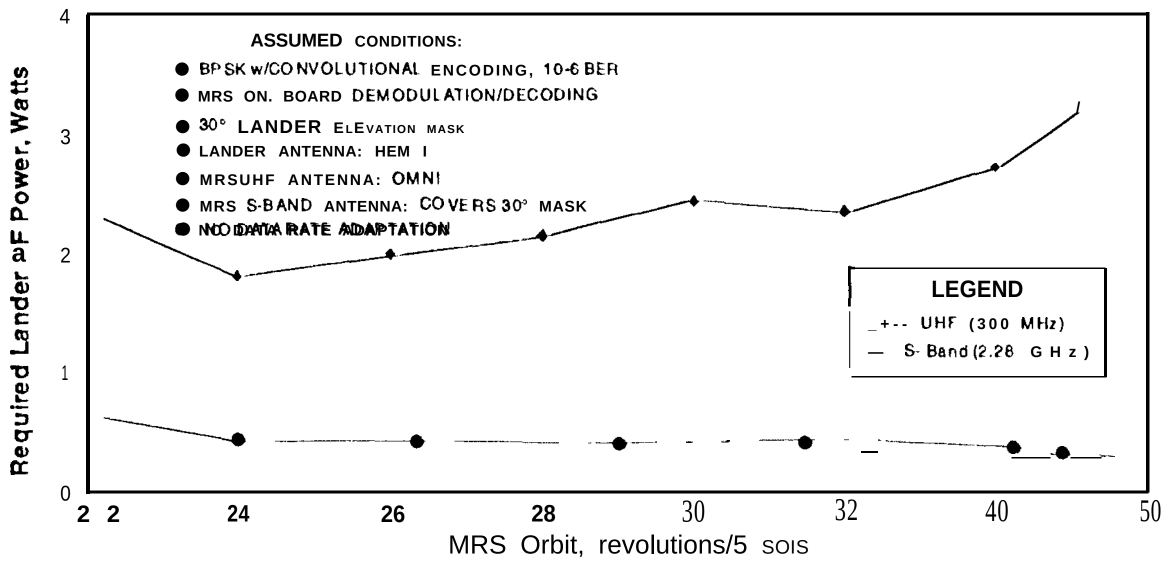

Figure 8. Required lander RF Power vs Various Circular, Sun-synchronous MRS Orbits and RF Frequency Band (10 Mb/sol/lander avg throughput/5 sols)

account both the variations in lander-to-MRS contact time across the surface of Mars and link performance estimates. The UHF and S-band curves assume a single lander-to-MRS data rate for each orbit type (no rate adaptation) and a lander hemispherical coverage antenna, but distinct MRS antenna types are assumed. As described above, UHF performance is generally substantial] y better than S-band performance for the primary antenna types of this study. Taking advantage of this difference, the UHF curve is based on use of a simple omnidirectional antenna on the MRS. The S-band curve, on the other hand, assumes use of a nadir oriented MRS antenna sized to cover the region defined by a 30° lander elevation mask -- achieving higher gain than an omni antenna, and partially offsetting the performance degradation resulting from the higher frequency.

Note that the two strategies illustrated in the. figure result in different trends in performance as the MRS orbit is varied. For UHF, with fixed lander and MRS antennas, performance tends to improve slightly as the orbit altitude is decreased (as the number of revolutions per sol increases). The opposite is generally true at S-band. For this curve, the MRS antenna is varied in size as the MRS altitude is varied in order to maintain coverage to the 30° mask region as described above. The changing antenna gain combined with the increase in contact time at higher altitudes results in a net improvement in performance. Ultimately, however, a limit is reached at which coverage to some points on the surface of Mars drops so low that this trend is reversed. (Note that this loss of coverage for the higher altitude orbits occurs in the polar regions due to the orbit inclination required to maintain sun-synchronization -- see Figure 1.) Optimum performance. at S-band, for the examined conditions, occurs for the MRS orbit completing 24 revolutions in 5 sols. A final selection between the various available frequency bands has not been made and may depend on factors other than data return performance. One such factor is the potential need for a backup lander-to-13arth communications mode in case of MRS failure. The Deep Space Network, which would be used in such a situation, currently implements both S-band and X-band return links making it highly desirable to use one of these frequencies for the Mars landers. Use of a single S-band frequency for both the lander-MRS and lander-Earth backup links could simplify the lander design.

This section has illustrated some of the key interrelationships between the MRS orbit and lander-to-MRS data return capability. For elliptical orbits, it was found that data rate variation on the lander-to-MRS link was key to maximizing data return potential. Additionally, it was found that no one orbit was optimum in the sense of maximizing lander data return in all situations. Instead, the optimum orbit depends on the details of the implementation which in turn depend on both performance and operational considerations. For this reason, the analyses are continuing with expansion of the trade space as additional factors are considered.

MARS-EARTH LINK OCCULTATIONS

Occultation of the communications link from the MRS to Earth occurs when the MRS passes behind Mars as viewed from Earth. During link occultation, communications between the MRS and the DSN will not be possible. Link occultations, depending on their frequency and duration, can be a significant factor impacting overall mission operations.

In evaluating the severity of link occultations, there are several distinct parameters of interest. Of greatest significance is the frequency of occultation events, herein expressed as the percentage of SOIS in which some occultation of the MRS-to-Earth link occurs. Obviously, if link occultation is an extremely rare event, its impact on mission operations and data return to Earth will be negligible. With frequent link occultations, mission operations will be routinely impacted. The aggregate amount of occultation time per sol defines the total communications time lost on the link to Earth. Depending on the amount of time lost, overall mission data return (or the operational complexity for assuring adequate mission data return) can be significantly impacted. Finally, the amount of time the MRS must be able to operate without communications with Earth is set by the durations of individual occultation events. In normal operations, the MRS will probably be expected to operate without communications with Earth up to a sol or more, but there may be some operational modes and emergency conditions which require more frequent contact. (One such mode could be a bent-pipe relay mode used for lander-to-Earth communications in the event of an MRS communications failure.)

Link occultations were examined in detail using computer simulation to estimate both the frequency of link occultations and their severity as a function of orbit type, Figure 9 summarizes some of the results obtained. The figure plots both the per event and aggregate occultation duration per sol as a function of the frequency of link occultation for a number of the orbit types examined. Both median and maximum occultation durations are included in the plot with the

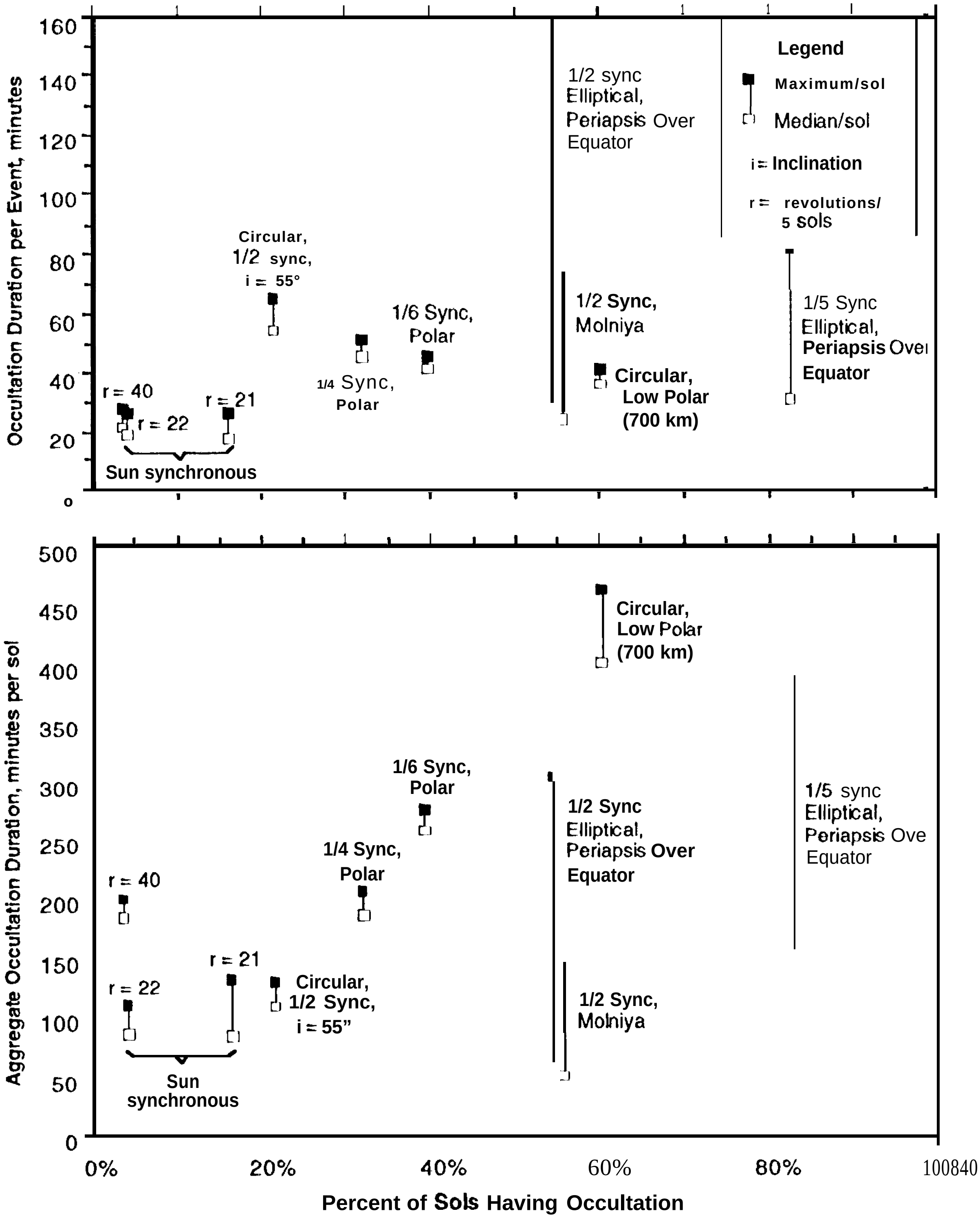

Figure 9. Statistics of MRS-to-Earth Link Occultations

aggregate median duration calculated only over those SOIS in which some link occultation occurred. For the sun-synchronous orbits, the right ascension of the ascending node is assumed to initially lie within 5° of the ideal position along the day-night terminator on Mars. By placing the node near the terminator, the plane of the orbit is nearly perpendicular to the line connecting Mars and the sun, thus minimizing the frequency and duration of link occultations.

For the orbits which are not sun-synchronous, the frequency of link occultation occurrence is, in general, set by the minimum MRS altitude occurring during the orbit. For the circular orbits, a lower altitude tends to reduce the duration of the. individual link occultations, but the greater number of orbits per sol causes more occultations resulting in a greater aggregate occultation duration. Greatest variability in occultation duration is exhibited by the elliptical orbits, with potentially very long occultation events occurring when the apoapsis portion of the orbit falls behind Mars as viewed from the Earth.

As illustrated, the sun-synchronous orbits have significantly better occultation performance than the other orbits examined. For these orbits, the ascending node rotates once about Mars each Mars year, so the plane of the orbit is always nearly perpendicular to the. line from Mars to the sun. Only a rare combination of events results in any occultations for these orbits. As seen from Mars, the Earth tends to move from side-to-side about the sun in the plane of the ecliptic. Since the equator of Mars is tilted with respect to the ecliptic plane, an observer on Mars would also scc, through the course of one Mars year, an apparent North-South motion of the Earth and sun as Mars revolves around the sun. It is a combination of the two effects that results in link occultation for the sun-synchronous orbits. That is, when the sun/Earth system is near its extreme northern or southern point as seen from Mars, and the Earth is off to the side of the sun, then link occultations can occur. Thus, occultations of the link from the MRS to Earth are ram, but not impossible, for the sun-synchronous orbits examined.

MARS RELAY SATELLITE SOLAR ECLIPSES

Solar eclipses occur when the MRS passes behind Mars as viewed from the sun. A key impact of an eclipse is loss of energy to the. MRS solar arrays -- forcing the MRS to use battery power for the duration of the eclipse event. Solar eclipses are a significant driver in establishing MRS battery requirements and must be taken into account when defining overall mission operations,

For the orbit types that are not sun-synchronous, the frequency and duration of solar eclipses will be similar to the frequency and duration of MRS-to-Earth link occultations. Because these orbits are in no way synchronized to the position of the sun or Earth, the relatively small differences in the positions of the sun and Earth, as seen from Mars, have little impact on observed performance. The results presented above for the circular and elliptical orbits that are not sun-synchronous are, to a good approximation, applicable when evaluating solar eclipse frequency and duration. Of greatest importance is the eclipse duration per event rather than the aggregate eclipse time per sol. The MRS battery design must be able to support operation through a complete eclipse (although some operations, such as communications with Earth, may be curtailed during an eclipse).

For the sun-synchronous orbits, there is a substantial difference between the frequency/duration of link occultations and the frequency/duration of solar eclipse events. As described above, link occultations occur only when an infrequent combination of Earth-Mars-sun geometry occurs. Because the Earth is not a factor during consideration of solar eclipse events, the side-to-side variation in position described above is irrelevant. That is, for an MRS orbit ascending node at or near the terminator, the sun will always be approximately perpendicular to the orbit plane. Simulations have revealed, for the sun-synchronous orbits, no solar eclipses will occur if the MRS ascending node is properly aligned. Only if the MRS ascending node is not accurately placed at the terminator will some solar eclipses occur.

Figure 10 quantifies this result. The curve of the figure shows, for a variety of circular, sun-synchronous orbits, how far the MRS ascending node can be from the day/night terminator before some solar eclipse events occur. Note that the orbits at lowest and highest altitude have.

somewhat smaller regions about the terminator that result in no eclipses. For the very low orbits (40 and 50 revolutions in 5 sols), it is possible for the small variations in Mars/sun/MRS geometry to cause a limb of the orbit to pass behind Mars as seen from the sun. The higher altitude orbits achieve worse than optimum performance due to their differing inclinations. In order to remain sun-synchronous, the MRS orbit inclination must be adjusted as the orbit altitude is increased. Eventually, the orbit plane tilts sufficiently close to the equator of Mars to cause the northern and southern extremities of the MRS orbit to pass behind Mars for some parts of the Mars year. For the examined sun-synchronous orbits, it appears likely that the MRS can be placed close enough to the terminator to entirely avoid solar eclipse. events during normal mission operations. Because eclipses cannot be avoided for the other orbit types, this result represents a substantial advantage for the sun-synchronous orbits.

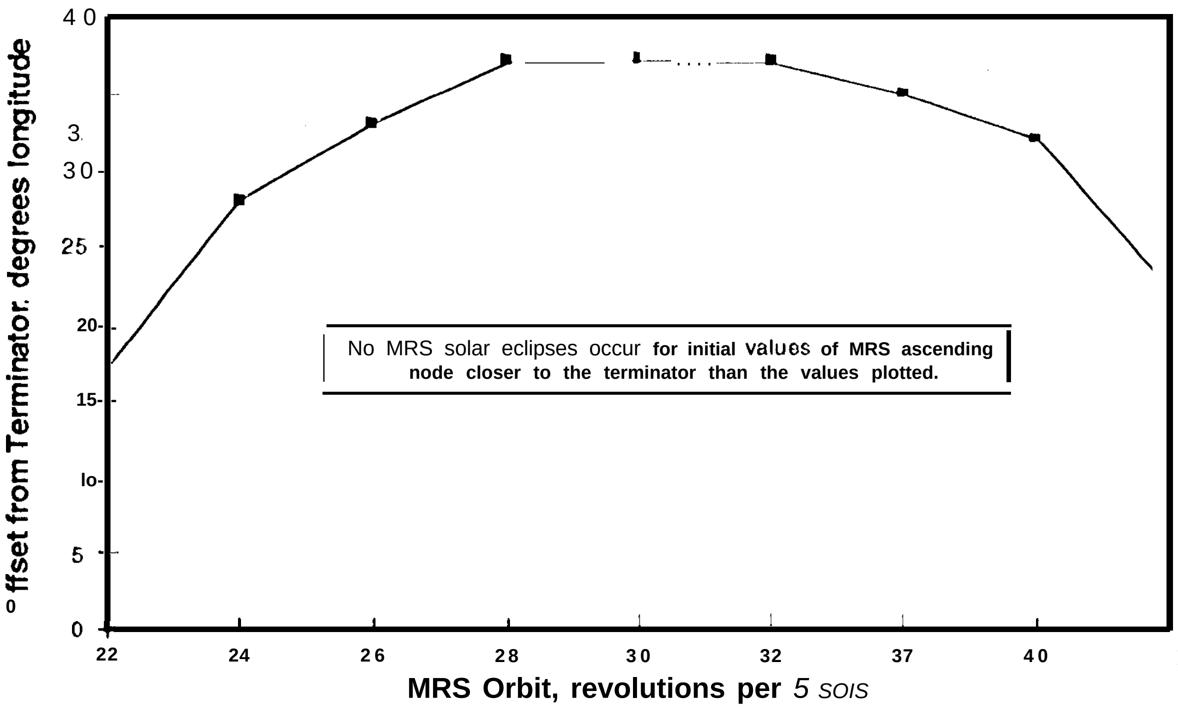

Figure 10. MRS Solar Eclipse Sensitivity to Initial MRS Ascending Node (For Various Circular, Sun-Synchronous MRS Orbits)

DELIVERY INTO ORBIT

A key consideration in the design of the Mars Relay Satellite is the mass which can be delivered into the desired orbit by a medium or intermediate launch vehicle such as the Delta II 7925 or the Atlas IIAS. The maximum dry mass of the spacecraft is a function of a number of factors, specifically the payload capability of the launch vehicle, the arrival conditions for the opportunity under consideration, navigation and orbit trim AV requirements, and the length of the launch period, For this analysis, it is assumed that a bipropellant system delivering an Isp of 308 sec. is used for the main engines. The Mars orbit into which the spacecraft is initially captured is an elliptical orbit with an altitude of 400 km and a period of 4 sols; a gravity loss of 5% is assumed during capture. In addition to the AV required for orbit insertion, the spacecraft must be able to supply 100 m/s for statistical navigation maneuvers during cruise and orbit trim maneuvers after arrival. A 20 day launch period is assumed, and a certain percentage of the nominal launch vehicle capability has been held back for launch vehicle contingency (10% for the Delta and 15% for the untested Atlas IIAS). Standard payload adapters have been assumed, amounting to 57 kg for the Delta and 65 kg for the Atlas. (It should be noted that these launch vehicle assumptions are somewhat conservative.) In addition to an assessment of the overall dry mass of the spacecraft, an estimate has been made of the “net mass”, i.e. the mass of the spacecraft which is not devoted to the propulsion system (main engine, tanks and structure). For this analysis, it is assumed that the mass of the propulsion system is equal to 69.7 kg + 11 .67% of the propellant mass. Approximately 2,7% of the propellant mass has been retained for holdup and reserve.

Representative Sun-Synchronous Orbit (22-rev/5-sol)

The final MRS orbit assumed for analysis is a nearly circular, sun-synchronous frozen orbit with a semimajor axis of 7616.292 km and an inclination of 125.S0. The ground track of this orbit repeats every 5 sols, during which time the spacecraft has orbited Mars 22 times. For each of the three Earth-Mars opportunities under consideration, 1998, 2001, and 2003, a number of trajectories have been generated which represent minimum total AV solutions for various launch dates. For each trajectory, the maximum total and net dry masses have been calculated for several assumed values of the propellant loading. As illustrated in Figure 10, these data can be expressed as curves of dry mass versus launch date, for given constant propellant masses. The end points of these curves are defined by solutions with zero launch margin. The desired solution is the value of the propellant loading which creates the largest dry mass over the 20 day launch period. Figure 11 illustrates the situation for the 1998 opportunity and a Delta launch vehicle. Each line is labeled with a different propellant mass, The heavy horizontal bars indicate. the optimal launch period, maximum dry masses (total and net) and approximate propellant load. Table 2 summarizes the mass results for all three opportunities, A listing of the optimum launch periods is included in the next section.

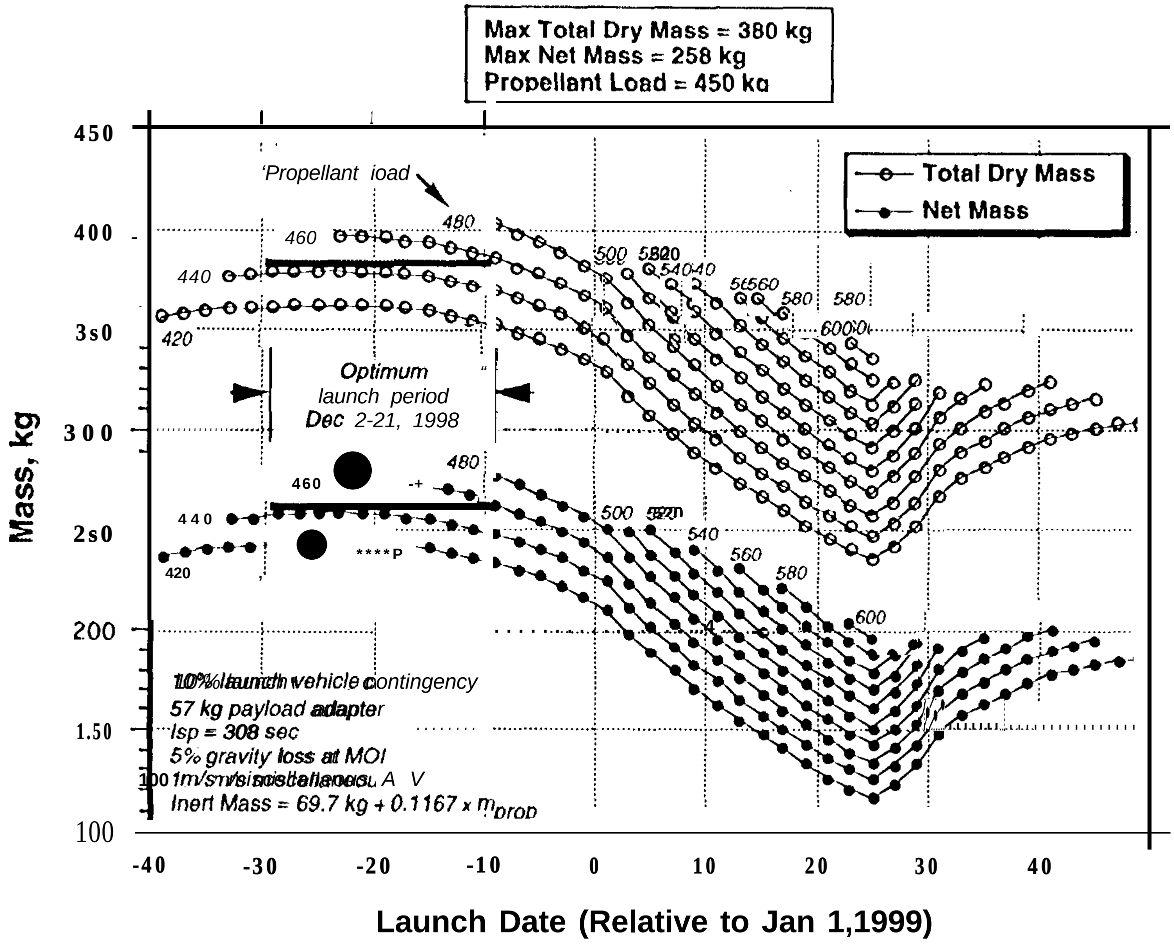

Figure 11. Maximum Dry Mass vs Launch Date for a Constant Propellant Load — 1998/99 Opportunity, Delta 792S, Sun-Synch 22-rev/S-sol Repeat Orbit

Table 2. MAXIMUM DRY MASS AND PROPELLANT LOAD

Opportunity	Launch Vehicle	Maximum Total Dry Mass, kg	Maximum Net Mass, kg	Propellant load, kg
1998	Delta 7925	380	2S8	450
	Atlas IIAS	705	537	840
2001	Delta 7925	350	207	625
	Atlas IIAS	650	444	1165
2003	Delta *7925*	*469*	*355*	*469*
	Atlas IIAS	870	701	792

Initial Orbit Orientation

Mission planning and execution are also affected by the initial orientation of the spacecraft's orbit. In particular, the location of the node relative to the day/night terminator influences the occultation characteristics and timing of communications periods relative to daylight surface operations. The target orbit inclination can be achieved by choosing either of two aim points at arrival. The purpose of this analysis was to identify the insertion strategy which places the orbit node as close as possible to the desired location on the terminator, Table.3 provides a summary of this analysis, indicating optimum launch/arrival pairs, launch energy (C3), declination of the launch asymptote (DLA), magnitude of any interplanetary deterministic AVS, and the arrival V_∞ (VHP). Also shown is the approach (North or South) which creates the. smallest initial offset from the desired terminator orbit, and the magnitude of the initial node offset. Results are shown for the. beginning, middle, and end of each 20 day launch period. The worst geometry occurs for the 1998 opportunity, where a maximum node offset of 24.9° occurs at the end of the launch period. The 2001 and 2003 opportunities both exhibit very favorable initial geometries. Eastward node offsets can be corrected without significant AV expenditure by initially placing the spacecraft into a highly elliptical "drift" orbit, whose node is nearly fixed inertially. As Mars orbits the sun, the terminator catches up with the spacecraft's orbital node at the rate of approximately 0.5° per day.

Table 3. ARRIVAL CONDITIONS AND GEOMETRY

Launch Date	Arrival Date	*C3,* km^2/s^2	DLA	BPM,** km/s	VHP, km/s	Insertion	Node Offset *
12-2-1998	9-10-1999	12.488	10.1°	-	3.347	South	10.9" West
12-11-1998	9-25-1999	10.878	14.9°	-	3.343	South	15.6° West
12-21-1998	10-3-1999	9.986	21.4°	-	3.399	South	24.9° West
3-3-2001	11-17-2001	5.256	-7.1 "	0.671	3.368	North	5.7" East
3-12-2001	11-s-2001	4.607	*-30.0°*	0.833	3.126	North	3.4° East
3-22-2001	11-6-2001	5.159	-30.1°	0.765	3.172	North	1.8" East
5-29-20(M	12-24-2003	9.228	-6,1"	-	2.716	South	7.0" East
6-10-2003	12-31-2003	8.851	-5.5°	-	2.699	South	4.3° East
6-18-2003	1-3-2004	9.432	-5.9"	-	2.702	South	1.4° East

* Angle from 6PM point to ascending node
** Broken plane. maneuver

Alternate Orbits

Many 5-sol repeat ground track, sun-synchronous frozen orbits exist which may be able to support lander communications. The post-capture. AV has been calculated for a set of these orbits which complete 18 to 50 orbital revolutions in the course of 5 sols. As indicated in Figure 12, the variation in post-capture. AV could be a significant factor in orbit selection for mass-constrained situations.

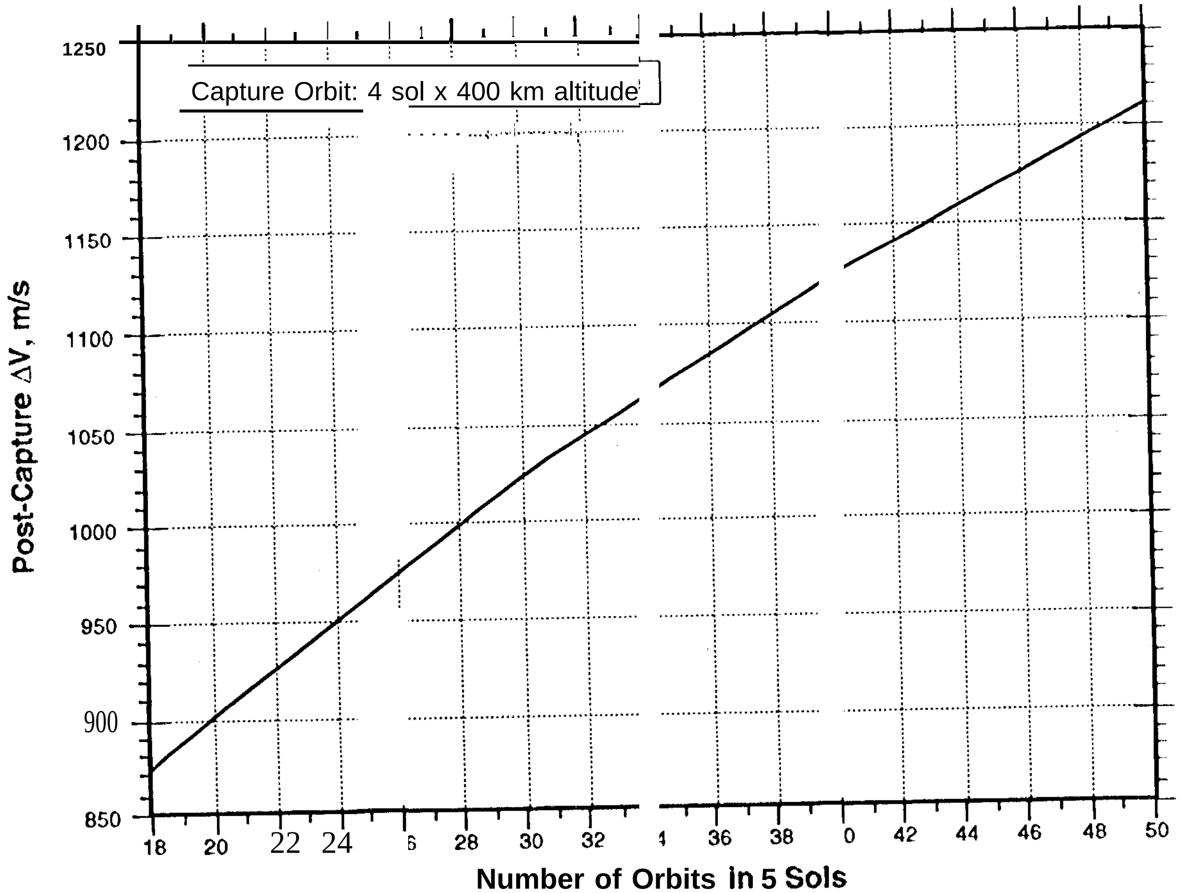

Figure **12. Post-Capture AV for Sun-Synchronous, 5-sol Repeat Frozen Orbits**

The orbits discussed thus far have all been near-circular, with eccentricities less than 0.006 Significant AV savings could be achieved through the use of elliptical orbits, assuming that the greater variability in communications geometry, compared with circular orbits, is acceptable. The 26-rev/5-sol repeat orbit with "critical" inclination of 63.4°, which was assumed in the Ames MESUR study,[5] has a post-capture AV requirement of approximately 630 m/s.[6] This would represent a AV savings of 300 m/s, compared with the 22-rev/5-sol near-circular, sun-synchronous orbit.

ORBIT STABILITY

One prime consideration in the design on an MRS orbit is the long term orbit stability. Frequent orbit maintenance maneuvers could significantly affect the total propellant requirement and complicate operations. Stability analyses indicate that two general classes of orbits are particularly suitable candidates.

The first class of orbits are sun-synchronous, frozen, multi-sol repeat orbits. These orbits have the same sun-relative geometry on every orbit and the same surface-relative geometry after every repeat period, A sun-synchronous repeat orbit has a stable semi-major axis and inclination as long as the orbit eccentricity remains constant. The eccentricity can be held constant if the initial eccentricity and argument of periapse are chosen to give a frozen orbit. The frozen orbit eccentricity depends upon the inclination and semi-major axis, but is less than 0.006 for the family of sun-synchronous, repeat orbits evaluated in this study. Refer to Figure 2 for the mean orbit altitude (semi-major axis minus the planet radius) and inclination for this family of sun-synchronous repeat orbits. The. stability of this general class of orbits is illustrated by the low amount of orbit maintenance propellant budgeted for the Mars observer mapping orbit: 40 m/s over two years.[7]

A second class of useful MRS orbits is multi-sol repeat orbits which have critical inclination. If the orbit inclination is either 63.4° or 116.6°, the long term variations in argument of periapse and eccentricity are zero regardless of the initial conditions. Consequently, a repeat ground track orbit at these inclinations will maintain the same surface relative geometry for each repeat period. In general, these orbits cannot be. sun-synchronous (a special case. of a near circular sun-synchronous orbit exists at 116.6° inclination for a orbit semi-major axis of about 7055 km). The stability of this general class of orbits is illustrated by the Molniya orbits around the Earth. These orbits are used for Earth communications satellites with high latitude coverage requirements and low orbit maintenance propellant allocations.

CONCLUSIONS

Orbit selection for global support of Mars robotic surface missions involves a complex, multi-dimensional trade space. Factors having important implementation and operational relevance include contact times, data return volume, Earth and sun occultations, MRS mass delivery capability into final orbit, orbit orientation, and orbit stability.

A family of near-circular, sun-synchronous, repeat orbits provides favorable candidates for global support by a relay satellite. The only significant factor which may requite consideration of another type of orbit is MRS mass delivery into final orbit. An elliptical orbit could be selected with lower delivery AV; however, this AV savings would probably be offset, at least partially, by increased orbit maintenance AV, especially if a long life communications resource is desired.

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